Scintillator based hybrid photon detector development for the KM3NeT (km^3-scale) deeep sea neutrino telescope

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Abstract

Scintillating crystal-based hybrid photon detectors (X-HPDs) have been demonstrated as viable single photon detectors since 1996 in the Lake Baikal neutrino telescope. Prior to this, the Philips XP2600 was developed under the DUMAND program, while more recently, developments at CERN have demonstrated the advantages of a true concentric geometry with a scintillator at the geometric centre of a spherical photocathode, giving almost 100% electrostatic collection efficiency over 3π solid angle coverage. We have started to develop a new series of quasi-spherical X-HPDs starting at 8" and progressing toward the maximum that can be fitting in a standard 17" optical pressure sphere for a future large deep sea neutrino telescope. The thrust of this R&D will be to investigate the industrialisation of the X-HPD to the point where it represents a significant cost reduction per cubic kilometre of instrumented volume compared to conventional PMTs, thereby allowing for extremely large telescope target volumes. Such gains will arise through an all-glass envelope, internal processing of a standard or enhanced bi-alkali photocathode, and either from cost reductions in the central scintillating crystal or the use of a deposited phosphor viewed by a small PMT. Details of the development program and recent progress in the characterisation of prototypes will be presented.

Key words: Scintillating Crystal, X-HPD, Hybrid single photon detector, Neutrino Telescope
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1. Introduction and background

Considerable interest has been rekindled in the use of crystal-based Hybrid Photon Detectors (X-HPDs) at future water neutrino detectors. Such devices operate a large photocathode at a high voltage of -20kV to accelerate photoelectrons toward a central anode electrode, beyond which a scintillating crystal is viewed through a glass window by a small photomultiplier (PM), located outside the primary vacuum volume. The combination of high scintillation light yield and short decay time - tens of nanoseconds - affords better time resolution than a large hemispherical PM of the same photocathode area. Scintillation gain improves 1st dynode statistics, allowing multi-photon counting beyond the two photon shoulder limit typically seen in large PMs [1]. The considerable experience obtained in more than ten years' operation of 200 'Quasar'(370mm diameter) X-HPD devices at the Lake Baikal neutrino detector demonstrated their viability and their intrinsic time resolution (transit time spread) of < 1ns rms. The all-glass Quasar 370 development

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Fig. 1. The Philips XP2600 X-HPD, constructed at the Philips Brive la Gaillard site: now Photonis S.A.S

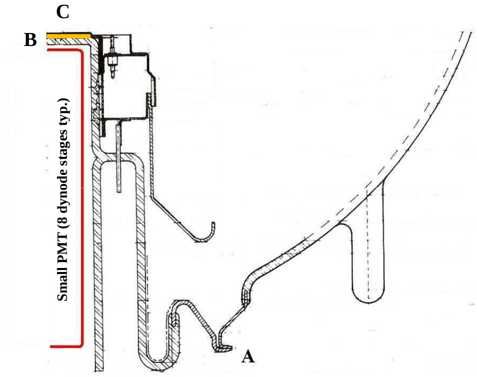

Fig. 2. Quadrant view of the anodic section of the XP2600 X-HPD showing the placement of the phosphor, viewing PM, anode electrode and envelope sealing (see text for details)

[1], [2], [3], [4] was based in part on the experience gained in construction and operation of around 30 Philips XP2600 ("Smart") (Fig. 1) 15" quasi-spherical X-HPDs [5], [6], [7]. Figure 2 illustrates the construction of the XP2600 anodic section. The device was of hybrid glass-metal construction with the almost spherical photocathode dome attached to a central glass insert, equipped with the integral viewing window, via a pair of orbitally-welded glass-to-metal seal rings (detail (A)). The disk-like scintillator geometry used P47 (Y2SiO5:Ce) phosphor deposited by sedimentation onto the glass viewing window (B). This technique had the advantage of avoiding a problematic crystal-to-glass seal had a solid scintillator disk been used. The aluminium anode electrode (C) was deposited on the scintillator and was thin enough (typically 100nm) that only a few KeV of incident 25KeV photoelectron energy was lost in traversing it. Since the photoelectrons penetrate only a few microns into the scintillator, a thin phosphor was sufficient. Since the Philips XP2600 and Quasar 370 both used a disk-like deposited phosphor scintillator, neither fully exploited the full advantage of a spherical geometry with a convex shaped scintillator at the geometric centre of the photocathode so dramatically demonstrated in recent studies at CERN [8], [9], [10], [11]. Such a geometry offers excellent (sub-ns) isochronicity and close to 100% electrostatic collection efficiency for drifting photoelectrons over 3π solid angle coverage, a performance significantly exceeding the figure of around 70% of photoelectrons arriving at the first dynode in a typical large hemispherical PMT having a much smaller (typically $3\pi/4$) solid angle coverage.

A further exploitable property in the concentric spherical geometry is the 'double-cathode' effect in which incoming photons passing chord-wise through the envelope have two chances to create detectable photoelectrons, giving a significant increase in effective quantum efficiency (Q.E.) [8]. In combination with almost 100% electrostatic collection efficiency over a 3π solid angle, the double cathode effect promises polar angle-averaged overall detection efficiencies around 40%, even using a standard (unenhanced) bialkali photocathode. These advantages, coupled with the insensitivity of the X-HPD to the Terrestrial magnetic field have motivated the renewed interest in these devices. Figure 3 illustrates the double cathode enhancement in Q.E. in recuperated Quasar and XP2600 tubes via a comparison of polar and equatorial illumination. The enhancement is significant, though less dramatic than the 50% seen in a true concentric X-HPD geometry [8].

2. Deep sea neutrino telescope sensitivity enhancement using X-HPDs

Figure 4 illustrates the possible gain in neutrino telescope detection efficiency as a function of energy for different optical module (OM) configurations. The sea floor geometry is a hexagon of 127 detection lines (each rising to 34 storeys separated by 15m), spaced at 85m intervals. A sea water absorption length of 35m between 300 & 600nm is assumed; characteristic of the ANTARES site [12]. The simulation used 'NESSY' [13] running under Mathematica, with up-going neutrinos in a cosine distribution.

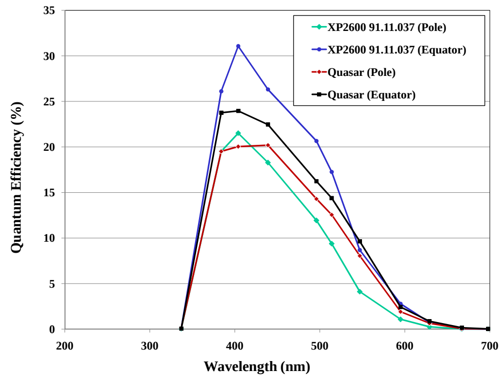

Fig. 3. Effective Q.E. gain by "double cathode" effect; polar and equatorial illumination of Quasar and XP2600 X-HPDs

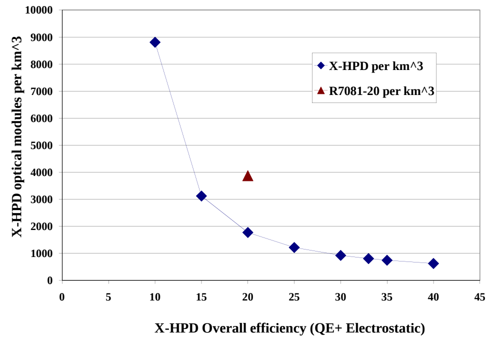

Fig. 5. N° of OMs per km^3, comparing the Hamamatsu 10" R7081-20 PM of ANTARES with same diameter X-HPDs of 3π solid angle coverage and overall efficiency up to 40%.

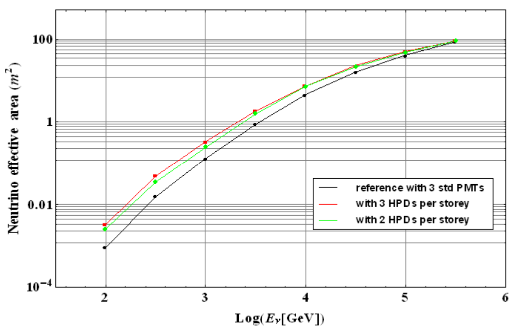

Fig. 4. Possible gain in deep sea neutrino telescope detection efficiency *vs* energy: X-HPDs replacing hemispherical PMs of identical area in various geometries (see text for details).

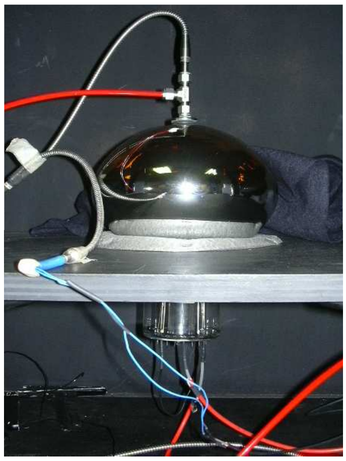

Fig. 6. X-HPD envelope demonstrator: all-glass construction with internally-processed bialkali photocathode.

Three OM configurations are compared:

– (A) ANTARES reference configuration:'triplet' of 10" Hamamatsu R7081-20 PMs with an assumed overall efficiency of 20% (Q.E. + electrostatic);
– (B) Two 10" X-HPDs with 40% overall efficiency over 3π solid angle, in a back-to-back ('peanut') orientation, each storey rotated 90° relative to the precedent.
– (C) Three 10" X-HPDs with the parameters of (B) mounted in the ANTARES 'triplet' geometry.

Figure 5 illustrates the reduced number of OMs per km^3 of telescope volume, comparing the R7081-20 PM($\pm$ 55° polar angle sensitivity) with X-HPDs of the same diameter having 3π solid angle coverage and varying overall detection efficiency. The improved performance of the X-HPD, including exploitation of the double cathode effect, allows a much larger volume to be instrumented.

3. X-HPD development for KM3NeT

Figure 6 illustrates the first X-HPD prototype of the present development. Its all-glass construction incorpores a central re-entrant glass tube terminated by a glass disk window through which a scintillator would be viewed in a fully equipped device.

The standard bialkali photocathode is internally processed, with all generators present in the tube; an essential step in X-HPD industrialisation. This prototype is not equipped with a scintillating crystal although a 2cm diameter metal plate anode allows photocurrent measurements of Q.E. and also

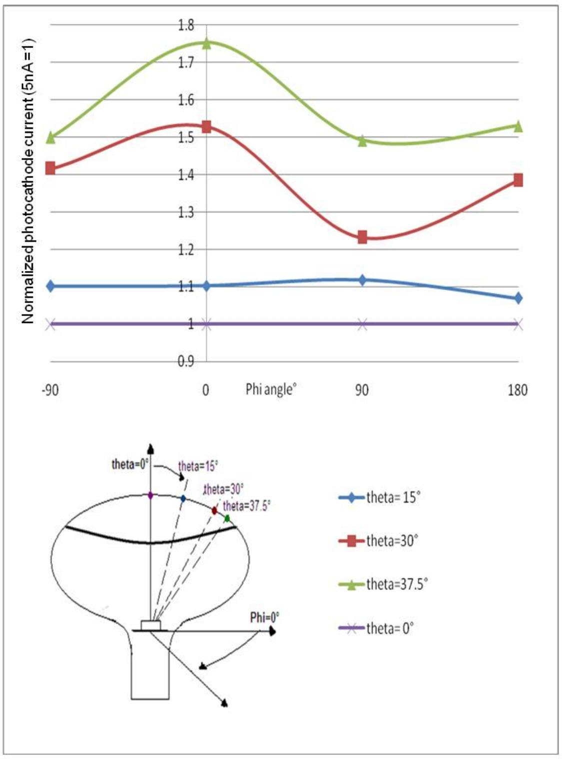

Fig. 7. X-HPD envelope demonstrator photocathode sensitivity at 9 positions in varying polar and azimuthal angle.

photocathode sensitivity mapping.

Figure 7 illustrates the photocathode relative sensitivity, measured using a Keithley 485 picoammeter, and a blue (475 nm) LED-fibreoptic *ventouse* attachment at nine positions in varying polar and azimuthal angles. Despite the limitation on the external photocathode acceptance of around 40°, significant double cathode enhancement is seen; partly from the photocathode overlaying the aluminium equipotential layer on the lower hemisphere, which enhances efficiency for the window acceptance. There does appear however to be an azimuthal variation in photocathode efficiency, which needs to be further investigated.

Figure 8 illustrates results from electrostatic studies performed on the envelope shape used in the prototype, using the Simion-8 [14] package. The worse case transit time difference for photoelectrons drifting to the anode plate from the pole of the tube and from the polar angle limit of 40° are shown. Above 5kV the transit time difference is less than 1ns.

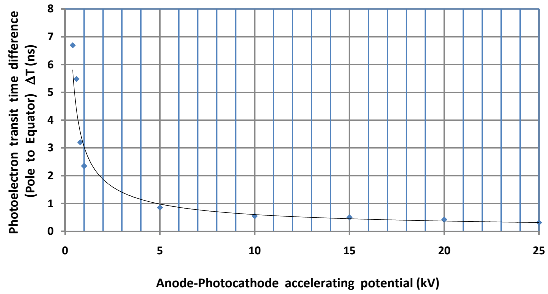

Fig. 8. Transit time difference (ns) for photoelectrons emitted at polar angles of 0° and 40°, using Simion8.

4. Conclusion and future plans

The Photonis-IN2P3 collaboration on new ν telescope X-HPD prototypes has demonstrated the first two critical steps toward industrialisation - an all glass envelope and full internnal bialkali photocathode processing. Development will continue through several more stages, and by the end of 2008 the first 8" X-HPD tubes with scintillator anodes will begin to be evaluated. During 2009 convergence toward the best-suited shaped crystal anode will be made from among a variety of fast, high yield crystals or deposited phosphors. The choice will be based on evaluation of prototype tubes with the focus on timing resolution, multiphoton separation, scintillation light extraction and cost considerations of deposited phosphors *vs* bulk crystals. By the end of 2009 it is planned to construct final-size prototype with diameters in the range 12-15" using the optimised scintillator.

5. Acknowledgements

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